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Is observed direct CP violation in $B_d \to K^+\pi^-$ due to new physics? Check standard model prediction of equal violation in $B_s \to K^-\pi^+$

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Abstract

The recently observed direct CP violation in $B_d \to K^+\pi^-$ has raised suggestions of possible new physics. A robust test of the standard model vs. new physics is its prediction of equal direct CP violation in $B_s \to K^-\pi^+$ decay. CPT invariance requires the observed CP violation to arise from the interference between the dominant penguin amplitude and another amplitude with a different weak phase and a different strong phase. The penguin contribution to $B_d \to K^+\pi^-$ is known to be reduced by a CKM factor in $B_s \to K^-\pi^+$. Thus the two branching ratios are very different and a different CP violation is expected. But in the standard model a miracle occurs and the interfering tree diagram is enhanced by the same CKM factor that reduces the penguin to give the predicted equality. This miracle is not expected in new physics; thus a search for and measurement of the predicted CP violation in $B_s \to K^-\pi^+$ decay is a sensitive test for a new physics contribution. A detailed analysis shows this prediction to be robust and insensitive to symmetry breaking effects and possible additional contributions.

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I. INTRODUCTION - CONDITIONS FOR CONCLUSIVE TESTS FOR NEW PHYSICS

The recent discovery of direct CP violation in $B_d \to K^+\pi^-$ decays has raised the question of whether this effect is described by the standard model or is due to new physics beyond the standard model [1]. Unfortunately a quantitative standard model prediction for the CP violation is impossible because of its dependence upon strong phases which cannot be calculated from QCD in the present state of the art.

A general theorem from CPT invariance shows [2] that direct CP violation can occur only via the interference between two amplitudes which have different weak phases and different strong phases. This holds also for all contributions from new physics beyond the standard model which conserve CPT. Thus the experimental observation of direct CP violation in $B_d \to K^+\pi^-$ and the knowledge that the penguin amplitude is dominant for this decay require that the decay amplitude must contain at least one additional amplitude with both weak and strong phases different from those of the penguin. The question now arises whether this additional amplitude is a standard model amplitude or a new physics amplitude.

A natural check for this question is to examine other related decays. The absence of CP violations found in the charged decay $B^+ \to K^+\pi^o$ immediately raised suggestions for new physics [1]. However, the reasons for relating the charged and neutral decays are not really serious. Although only the spectator quark is different, the CP violation can very different.

A more serious and detailed investigation [3] has recently been presented. Here we propose checking specifically those other decays where the standard model predicts an equal or related direct CP violation and where the prediction satisfies the following two conditions:

1. If experiment agrees with the prediction it will be difficult to find a new physics explanation. Thus new physics is ruled out for this particular direct CP violation.

2. If experiment disagrees with the prediction it will be difficult to fix up the standard model to explain the disagreement.

This leads directly to the $B_s \to K^-\pi^+$ decay, whose branching ratio is much smaller than that for $B_d \to K^+\pi^-$, and where the CP violation might be expected to be very different. Yet the standard model predicts equal direct CP violation.

We first note that the equality follows from a "miracle" which occurs in the standard model and is not expected in common new physics models; namely a relation [4] between the CKM matrix elements, in which the tree diagram contribution is enhanced by exactly the same factor that the dominant penguin contribution is reduced. Thus altough the branching ratio for the B_s decay which depends upon the dominant penguin contribution is reduced relative to the B_d decay, the direct CP violation remans the same.

This miracle is specifically relevant to the standard model and not expected if the CP violation arises from interference between the penguin contribution and a new physics contribution without the same dependence upon CKM matrix elements.

If on the other hand the experiment disagrees strongly with the prediction we note and will show below that the prediction depends upon minimum assumptions whose validity can be carefully checked. It will be very difficult to "fix" the standard model to explain the disagreement.

Thus the experimental search for CP violation in $B_s \to K^-\pi^+$ decay can provide convincing crucial information regarding the pesence or absence of new physics in these decays.

To put this argument on a firm foundation we generalize the U-spin symmetry prediction [4,5] that the recently observed direct CP violation in the $B_d \to K^+\pi^-$ decay must be matched by approximately equal direct CP violation in $B_s \to K^-\pi^+$ decay, even though the branching ratios can be very different. The result for this particular decay to charge conjugate final states can be obtained by standard model arguments which do not require full SU(3) or U spin symmetry, are nearly independent of detailed models and require only charge conjugation invariance for all final state rescattering.

II. SIMPLIFICATIONS IN $B_D \to K^+\pi^-$ AND $B_S \to K^-\pi^+$ DECAYS

The particular $B_d \to K^+\pi^-$ and $B_s \to K^-\pi^+$ decays are much simpler than the other decays considered [4] in the full U-spin multiplets.

1. The final states are charge conjugate. All strong final state rescattering and their relative phases remain related by the unbroken charge conjugation symmetry.

2. The final states are isospin mixtures with a relative phase between the two isospin amplitudes which is changed in an unknown manner by strong final state rescattering. Unbroken charge conjugation invariance preserves the phase relations between transitions to charge conjugate states. SU(3) symmetry breaking destroys phase relations between transitions to U-spin rotated states that are not charge conjugate; e.g. between $K\pi$, $\pi\pi$ and $K\bar{K}$ states.

3. The spectator quark flavor cannot be changed in these decays with one and only one quark of this flavor in both the initial and final states. This eliminates all diagrams in which the spectator quark participates in the weak vertex.

These simplifictions enable a much more robust derivation of the standard model prediction. Experimental violations will provide much more robust indications of new physics than other previously cited indications for new physics [1] based on predictions which assume U-spin symmetry, factorization or neglect of certain diagrams.

These simplifications are not present in the charged decay $B^+ \to K^+\pi^o$ where the final state can contain two u quarks which have the same flavor as the u spectator quark. In this decay other diagrams can occur with participation of the spectator quark; e. g. the annihilation diagram and the color-suppressed tree diagram. These both depend upon the same CKM matrix elements as the color-favored tree diagram. Thus although they can be small in comparison with the dominant penguin diagram, they can easily combine with the smaller color-favored tree diagram to produce a total amplitude proportional to the same CKM matrix factor as the tree diagram with a very different strong phase and therefore a very different CP violation.

III. SIMPLIFICATIONS FROM CKM PROPERTIES AND CHARGE CONJUGATION INVARIANCE

General properties of the CKM matrix in the standard model show [4] that the amplitude for the $B_d \rightarrow K^+\pi^-$ decay is the sum of two amplitudes proportional respectively to the products of CKM matrices $V_{ub}^* \cdot V_{us}$ and $V_{cb}^* \cdot V_{cs}$.

$$A(B_d \rightarrow \pi^- K^+) = V_{ub}^* \cdot V_{us} \cdot T_d + V_{cb}^* \cdot V_{cs} \cdot P_d \tag{1}$$

where T_d and P_d are two independent amplitudes labeled to correspond with the tree and penguin amplitudes in the conventional description, but with no dynamical assumptions. Eq. (1) is identical to eq. (2) of ref [4], with the amplitudes A_u and A_c of ref [4] replaced by T_d and P_d. The corresponding charge conjugate amplitude is

$$A(\bar{B}_d \rightarrow \pi^+ K^-) = V_{ub} \cdot V_{us}^* \cdot \bar{T}_d + V_{cb} \cdot V_{cs}^* \cdot \bar{P}_d \tag{2}$$

where $\bar{T}_d$ and $\bar{P}_d$ are two more independent amplitudes

The direct CP violation observed is proportional to the product $\mathrm{Im}(V_{ub}^* \cdot V_{us} \cdot V_{cb} \cdot V_{cs}^*)$

Similarly, the amplitudes for the $B_s \rightarrow K^-\pi^+$ decay and the charge conjugate decay can be written

$$A(B_s \rightarrow \pi^+ K^-) = V_{ub}^* \cdot V_{ud} \cdot T_s + V_{cb}^* \cdot V_{cd} \cdot P_s \tag{3}$$

$$A(\bar{B}_s \rightarrow \pi^- K^+) = V_{ub} \cdot V_{ud}^* \cdot \bar{T}_s + V_{cb}^* \cdot V_{cd} \cdot \bar{P}_s \tag{4}$$

where T_s, P_s, $\bar{T}_s$, and $\bar{P}_s$ are all independent amplitudes. Our equations (1 - 4) differ from the corresponding equations (4-7) of ref [4] by keeping all eight amplitudes independent and not introducing the SU(3) symmetry assumptions of ref [4].

The direct CP violation hopefully to be observed is proportional to the product $\mathrm{Im}(V_{ub}^* \cdot V_{ud} \cdot V_{cb} \cdot V_{cd}^*)$.

Although the individual terms in the B_d and B_s decays are very different and the branching ratios for the $B_d \rightarrow K^+\pi^-$ and $B_s \rightarrow K^-\pi^+$ decays are very different, Gronau has shown [4] that the two relevant products of CKM matrix elements satisfy the relation

$$Im(V_{ub}^* \cdot V_{ud} \cdot V_{cb} \cdot V_{cd}^*) = -Im(V_{ub}^* \cdot V_{us} \cdot V_{cb} \cdot V_{cs}^*) \tag{5}$$

Since the strong interactions for the transition between the quark level and the final hadron states are invariant under charge conjugation, and the final states are charge conjugate, all relevant products of TP amplitudes can be expected to be approximately equal and the CP violation to be approximately equal for the two transitions. The validity of this assumption of approximate equality is discussed in detail below.

We now first show how this equal CP violation follows from the conventional description in which the two terms are called penguin and tree diagrams and the $B_d \rightarrow K^+\pi^-$ and $B_s \rightarrow K^-\pi^+$ decays are U-spin mirrors related by SU(3). We then present a more general derivation in which the detailed dynamics of the two terms are not needed, all diagrams proportional to these two CKM factors are automatically included and full SU(3) symmetry is not required.

IV. THE U-SPIN PREDICTION WITH PENGUINS AND TREES

A large number of SU(3) symmetry relations between B_d and B_s decays to charge conjugate final states [6] were obtained by extending the SU(3) symmetry relations found by Gronau et al [7]. This can be seen at the quark level by noting the quark couplings in the penguin and tree diagrams for $B_d \to K^+\pi^-$ and $B_s \to K^-\pi^+$ decays related by the $d \leftrightarrow s$ U-spin [8] Weyl reflection:

$$B_d(\bar{b}d) \to_{penguin} (\bar{s}dG) \to_{strong} K^+\pi^-; \qquad B_s(\bar{b}s) \to_{penguin} (\bar{d}sG) \to_{strong} K^-\pi^+ \tag{6}$$

$$B_d(\bar{b}d) \to_{tree} (u\bar{s})(\bar{u}d) \to_{strong} K^+\pi^-; \qquad B_s(\bar{b}s) \to_{tree} (u\bar{d})(\bar{u}s) \to_{strong} K^-\pi^+ \tag{7}$$

Although the weak penguin and tree transitions from the initial state to the intermediate quark state are very different for B_d and B_s decays, the subsequent strong hadronizations from the intermediate quark state to the final hadronic state are strong interactions approximately invariant under SU(3) and its U-spin subgroup and exactly invariant under charge conjugation. They are expected to be equal for the B_d and B_s transitions into final states which are both U-spin mirrors and charge conjugate. The analysis of SU(3) relations in B decays has recently been updated [4,5,9] and applied to CP asymmetries in B_d and B_s decays. However, the particular role of charge conjugate final states has not been emphasized.

The penguin and tree contributions to B_d and B_s decays are proportional to very different CKM factors and have different strong interactions. These differences introduce unknown parameters in any analysis. Thus even though the strong interactions are approximately invariant under SU(3) and its U-spin subgroup and are exactly invariant under charge conjugation, the branching ratios and decay rates for the B_d and B_s decays depend upon unknown combinations of the different tree and penguin amplitudes.

However, Gronau's theorem (5) shows [4] that the products of the tree and penguin contributions for B_d and B_s decays relevant to direct CP violation are approximately equal with opposite sign. Thus the direct CP violation observed in $B_d \to \pi^-K^+$ is related to the as yet unobserved CP violation in $B_s \to \pi^+K^-$.

V. POSSIBLE COMPLICATIONS FROM OTHER DIAGRAMS LIKE CHARMING PENGUINS

A very different approach often called "charming penguins" suggests significant contributions from final state interactions which produce a $K\pi$ final state by strong rescattering from a $D^*\bar{D}_s^*$ intermediate state [10]. It is difficult to obtain a reliable quantitative estimate of these contributions along with their sensitivity to U-spin breaking, in particular for the strong phase which is crucial for CP violation. But these contributions can be appreciable [10]. The experimental branching ratio [11] for $B_d \to D^{*+}\bar{D}_s^*$ is a thousand times larger than the branching ratio for $B_d \to K^+\pi^-$.

$$BR(B_d \to D^{*+}\bar{D}_s^*) = (1.9 \pm 0.5)\%; \qquad BR(B_d \to K^+\pi^-)(1.85 \pm 0.11) \times 10^{-5} \tag{8}$$

Thus a very small rescattering of this large amplitude can have a serious effect on the strong interaction phase of the $B \to K\pi$ penguin amplitude. Our present treatment avoids

any quantitative estimate of the detailed dynamics of "charming penguins". The sum of all such contributions which are tree diagrams producing a $c\bar{c}$ pair subsequently annihilated by a strong final state interaction is called an "effective penguin diagram" because its dependence on the CKM matrix elements is the same as that of the normal penguin.

$$B_d(\bar{b}d) \rightarrow_{pengeff} (\bar{c}d)(c\bar{s}) \rightarrow_{strong} \bar{D}^{*-}D_s^* \rightarrow_{strong} K^+\pi^- \tag{9}$$

$$B_s(\bar{b}s) \rightarrow_{pengeff} (\bar{c}s)(c\bar{d}) \rightarrow_{strong} D^{*+}\bar{D}_s^* \rightarrow_{strong} K^-\pi^+ \tag{10}$$

All our subsequent analysis holds when the contribution of this "effective penguin" diagram is included. However other results for direct CP violation which depend upon U-spin relations between transitions to states which are not charge conjugates can suffer serious errors due to SU(3) symmetry breaking. A symmetry breaking which produces effects of order 10 or 20 per cent in branching ratios can produce large effects in relative strong phases which are crucial for direct CP violations.

In particular we note that the "effective penguin" contribution to $B_d \rightarrow \pi^+\pi^-$ of the U-spin analog of (9)

$$B_d(\bar{b}d) \rightarrow_{pengeff} (\bar{c}d)(\bar{c}d) \rightarrow_{strong} D^{*+}\bar{D}^{*-} \rightarrow_{strong} \pi^+\pi^- \tag{11}$$

is expected to be much less than in the case of $B_d \rightarrow K^+\pi^-$. The experimental branching ratio [11] for $B_d \rightarrow D^{*+}\bar{D}^{*-}$ is only 180 times larger than the branching ratio for $B_d \rightarrow \pi^+\pi^-$ instead of a thousand.

$$BR(B_d \rightarrow D^{*+}\bar{D}^{*-}) = (8.7 \pm 1.8) \times 10^{-4}; \qquad BR(B_d \rightarrow \pi^+\pi^-) = (4.8 \pm 1.8) \times 10^{-6} \tag{12}$$

VI. A GENERAL FORMULATION WITH MINIMUM ASSUMPTIONS

We now present a general formulation with the minimum assumptions necessary to predict the CP violation to be observed in $B_s \rightarrow \pi^-K^+$.

The following simplifying features of the $B_d \rightarrow \pi^-K^+$ and $B_s \rightarrow \pi^+K^-$ decays enable relating these decays without the U-spin assumptions needed in the general case.

1. The spectator flavor is conserved in the transition and cannot participate in a weak transition which necessarily involves flavor change. Thus the weak transition involves only a weak $b \rightarrow q_f U\bar{U}$ or $\bar{b} \rightarrow \bar{q}_f U\bar{U}$ decay, where U denotes either u, c or t and q_f denotes s for B_d decays and d for B_s decays

2. Each decay amplitude can be described by two terms proportional to two different products of CKM matrices. This is a general result following from the flavor properties of the three b or $\bar{b}$ decays noted above and the unitarity of the CKM matrix. This description is expressed formally by eqs. (1 - 4) where the labels T and P by analogy to the tree and penguin labels in the conventional description imply no assumption of tree or penguin dynamics. Eqs. (1 - 4) include all possible additional amplitudes allowed by the standard model including electroweak and charming penguins.

3. Direct CP violation can be observed only if the squares of these amplitudes contain a product of two CKM matrix elements with different weak phases and different strong phases.

4. Only four independent products of four CKM matrix elements are relevant to direct CP violation.

5. Our knowledge of QCD does not yet enable calculating strong phases; however, the experimental observation of direct CP violation in $B_d \to \pi^- K^+$ decays provides the information that the two terms must have different strong and weak phases.

So far there are no additional assumptions beyond those in the standard model. We now list our other basic assumptions:

1. The amplitudes for all these decays factorize into a weak transition described by products of CKM matrices and a strong factor invariant under charge conjugation. Thus for transitions to two charge conjugate final states denoted by f and $\bar{f}$

$$T_d(f) = \bar{T}_d(\bar{f}) \equiv T(f); \quad P_d(f) = \bar{P}_d(\bar{f}) \equiv P(f) \tag{13}$$

2. The mass difference between B_s and B_d is negelected. Thus decays to the same and to charge conjugate final states have the same energy for B_s and B_d decays and the same strong decay factors $T(f)$ and $P(f)$.

$$T_s(f) = \bar{T}_s(\bar{f}) = T(f); \quad P_s(f) = \bar{P}_s(\bar{f}) = P(f); \tag{14}$$

3. We neglect some hopefully small other U-spin-breaking effects arising from the B_s-B_d mass difference and the difference between pion and kaon form factors.

   - The mass difference produces intermediate quark states and final $K\pi$ states with slightly different energies and momenta. We neglect this dependence except for a small phase space correction.
   - All transitions involve the product of a pion form factor and a kaon form factor. These form factors are all equal in the U-spin symmetry limit and differences arising from symmetry breaking have been analyzed [4]. The tree-penguin interference term relevant to direct CP violation is proportional to the product of four form factors, one of which is a pointlike form factor of the meson created from a $q\bar{q}$ pair produced at the weak vertex of the tree diagram and the other three are hadronic. The dominant symmetry-breaking in these products between B_d and B_s decays is in the difference between the products of a pointlike kaon and a hadronic pion form factor for B_d decay and of a pointlike pion and a hadronic kaon form factor for B_s decay. We neglect this symmetry-breaking here, but note that the error introduced is expected to be real and not change the relative phase of diagrams which is crucial for CP violation. The error can also be estimated from simple models or detemined from other experiments [4].

- These are the only assumptions slightly related to U-spin. No other symmetry between pions and kaons is assumed.

4. The CKM matrices satisfy [4] Gronau's theorem (5)

We can immediately conclude that the strong and weak relative phases of the two terms in the $B_d \to \pi^- K^+$ decay amplitude are equal to the corresponding relative phases in the $B_s \to \pi^+ K^-$ decay amplitude, even though the magnitudes of these amplitudes are very different.

We now calculate the direct CP violation explicitly. Because the CKM factors are different, the U-spin symmetry breaking by the CKM matrices is different for the tree and penguin contributions. Thus simple U-spin relations have not been obtained [6,7] for branching ratios of transitions where both contributions are appreciable.

The direct CP violation in charmless strange B_d and B_s decays to charge conjugate final states is insensitive to these problems [4]. Direct CP violation is proportional to interference terms which depend upon the CKM matrix elements via the products related by Gronau's theorem eq. (5). Thus the B_d and B_s CP violations each depend upon a single CKM parameter, products insensitive to the ratio of the tree and penguin contributions and related by eq. (5). The CP violations in B_d and B_s decays to states which are charge conjugates and U-spin mirrors thus depend to a good approximation on equal single parameters.

Squaring eqs. (1 - 4) and substituting eqs. (13 - 14) give the direct CP violations for $B_s \to K^- \pi^+$ and $B_d \to K^+ \pi^-$

$$|A(B_d \to \pi^- K^+)|^2 - |A(\bar{B}_d \to \pi^+ K^-)|^2 = 4\mathrm{Im}(\mathrm{V_{ub}^*} \cdot \mathrm{V_{us}} \cdot \mathrm{V_{cb}} \cdot \mathrm{V_{cs}^*}) \cdot \mathrm{Im}(\mathrm{T} \cdot \mathrm{P}^*) \tag{15}$$

$$|A(B_s \to \pi^+ K^-)|^2 - |A(\bar{B}_s \to \pi^- K^+)|^2 = 4\mathrm{Im}(\mathrm{V_{ub}^*} \cdot \mathrm{V_{ud}} \cdot \mathrm{V_{cb}} \cdot \mathrm{V_{cd}^*}) \cdot \mathrm{Im}(\mathrm{T} \cdot \mathrm{P}^*) \tag{16}$$

Eqs. (15) and (16) satisfy the CPT constraint [2] that the direct CP violation vanishes unless the amplitude contains two contributions for which both the weak and strong phases are different.

Combining Gronau's equality (5) with eqs. (15) and (16) gives

$$|A(B_s \to \pi^+ K^-)|^2 - |A(\bar{B}_s \to \pi^- K^+)|^2 = |A(\bar{B}_d \to \pi^+ K^-)|^2 - |A(B_d \to \pi^- K^+)|^2 \tag{17}$$

Since the individual tree and penguin contributions to U-spin conjugate B_d and B_s decays are very different and their branching ratios and lifetimes are different, the equality (17) does not apply to the expressions A_{CP} commonly used to express CP violation. Instead we have

$$A_{CP}(B_s \to \pi^+ K^-) = A_{CP}(\bar{B}_d \to \pi^+ K^-) \cdot \frac{BR(B_s \to \pi^+ K^-)}{BR(\bar{B}_d \to \pi^+ K^-)} \cdot \frac{\tau(B_d)}{\tau(B_s)} \tag{18}$$

where BR denotes branching ratio and τ denotes lifetime.

The same derivation applies to decays to any higher K^* resonance and any nonstrange isovector resonance.

$$A_{CP}(B_s \to \pi^{*+} K^{*-}) = A_{CP}(\bar{B}_d \to \pi^{*+} K^{*-}) \cdot \frac{BR(B_s \to \pi^{*+} K^{*-})}{BR(\bar{B}_d \to \pi^{*+} K^{*-})} \cdot \frac{\tau(B_d)}{\tau(B_s)} \tag{19}$$

Since CPT requires that the lifetimes and total widths of the B_d and $\bar{B}_d$ must be equal, the observed direct CP violation (15) must be compensated by an equal and opposite direct CP violation in other B_d decays. Furthermore, since CPT requires direct CP violation to vanish in any eigenstate of the strong S matrix [2], this compensation must occur in the set of states connected to π^+K^- by strong rescattering. Since parity is conserved in strong interactions this excludes all odd parity states.

It is not clear whether this compensation is spread over a large number of multiparticle states or is dominated by a few quasi-two-body states. It will be interesting to check this experimentally. In the toy model of ref. [2] the compensation occurs in the $\pi^o\bar{K}^o$ state connected to π^+K^- by charge exchange scattering. The next low mass allowed state is the vector-vector state.

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